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Phytoremediation approaches for restoration of pesticide-contaminated agricultural soils

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Abstract

In the western Cerrado region of Mato Grosso, decades of intensive soybean and cotton production have left measurable residues of atrazine, chlorpyrifos, and endosulfan in agricultural topsoils, raising concerns about groundwater contamination and long-term soil biological function. This research evaluated six candidate phytoremediation species—vetiver grass, sunflower, Indian mustard, maize, sorghum, and tall fescue—for their capacity to reduce concentrations of these three pesticides in contaminated field soils at the EMBRAPA Cerrados research station near Brasília, Brazil. Plants were established in a randomized complete block design on soils spiked with environmentally relevant concentrations of each pesticide and monitored over 90 days. Vetiver grass achieved the highest removal efficiency for atrazine (78.4%), while Indian mustard was most effective against chlorpyrifos (67.8%). Removal rates for endosulfan were generally lower, with vetiver again leading at 64.8%. Rhizosphere microbial activity, measured as dehydrogenase and fluorescein diacetate hydrolysis, was 2.3–4.1 times higher in planted versus unplanted controls, confirming rhizodegradation as a major contributing mechanism. These findings demonstrate that phytoremediation using locally adapted species offers a practical, low-cost strategy for restoring pesticide-contaminated Cerrado soils.

Keywords: Phytoremediation, pesticide contamination, atrazine, chlorpyrifos, endosulfan, vetiver grass, rhizodegradation, Cerrado soils, soil restoration, dehydrogenase activity

Introduction

Picture a soybean field in Mato Grosso after 25 years of continuous cropping: the yields remain profitable, but soil analyses reveal persistent residues of atrazine at 0.8 mg kg^{-1} and chlorpyrifos at 0.3 mg kg^{-1} —concentrations that exceed Brazilian intervention values and threaten the shallow aquifer that supplies downstream communities^[1, 2]. This scenario, increasingly common across the Cerrado biome, illustrates why pesticide contamination of agricultural soils has become a priority environmental concern in tropical developing nations.

Conventional remediation technologies—soil excavation, chemical oxidation, thermal desorption—are prohibitively expensive for the vast areas involved in tropical agriculture, with costs ranging from US\$50 to US\$500 per cubic meter^[3]. Phytoremediation, the use of living plants and their associated rhizosphere microorganisms to degrade, extract, or immobilize contaminants, offers a cost-effective and ecologically compatible alternative at roughly US\$5–15 per cubic meter^[4, 5]. Several mechanisms operate simultaneously: phytoextraction (root uptake and translocation), rhizodegradation (microbial breakdown stimulated by root exudates), phytostabilization (immobilization in the root zone), and phytovolatilization (transpiration of volatile metabolites)^[6].

Despite growing evidence for phytoremediation of heavy metals and petroleum hydrocarbons, fewer investigations have targeted pesticide-contaminated agricultural soils under tropical conditions, and almost none have compared multiple plant species against multiple pesticide classes in a single field experiment^[7, 8]. This research evaluated six plant species representing grasses, brassicas, and crops for their ability to remediate soils contaminated with atrazine (triazine herbicide), chlorpyrifos (organophosphate insecticide), and endosulfan (organochlorine insecticide)—three compounds with contrasting chemical properties and degradation pathways.

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Research area description

The experiment was conducted at the EMBRAPA Cerrados research station, located 35 km Northeast of Brasília, Federal District, Brazil (15°36'S, 47°42'W, elevation 1,014 m). The station sits within the core Cerrado biome on a well-drained Latossolo Vermelho (Ferralsol, FAO classification) developed from Tertiary laterite. Topsoil (0-20 cm) properties were: clay 58%, silt 14%, sand 28%, pH (H₂O) 5.4, organic carbon 22.7 g kg⁻¹, CEC 8.6 cmol₂ kg⁻¹. The regional climate is tropical savanna (Köppen Aw) with a distinct wet season (October-March, ~1,450 mm) and dry season (April-September, ~100 mm). Mean annual temperature is 21.3 °C [9].

Soil and water quality analysis

Baseline soil contamination was characterized by collecting 40 georeferenced samples (0-30 cm) across the experimental area in February 2023. Pesticide concentrations were determined by QuEChERS extraction followed by GC-MS/MS (Agilent 7890B/7000D) with detection limits of 0.005, 0.002, and 0.003 mg kg⁻¹ for atrazine, chlorpyrifos, and endosulfan, respectively. Soil biological activity was assessed through dehydrogenase activity (TTC reduction method), fluorescein diacetate (FDA) hydrolysis, and microbial biomass carbon (fumigation-extraction). Groundwater monitoring wells (3 m depth) at four plot corners were sampled monthly for pesticide residues using

solid-phase extraction and LC-MS/MS [10].

Materials and Methods

The experiment used a randomized complete block design with four replications. Seven treatments comprised six plant species (vetiver grass, *Chrysopogon zizanioides*; sunflower, *Helianthus annuus*; Indian mustard, *Brassica juncea*; maize, *Zea mays*; sorghum, *Sorghum bicolor*; tall fescue, *Festuca arundinacea*) and an unplanted control. Individual plots (3 m × 4 m) were established on naturally contaminated soil supplemented with additional pesticide solution to achieve uniform starting concentrations of 2.0 mg kg⁻¹ atrazine, 1.0 mg kg⁻¹ chlorpyrifos, and 0.5 mg kg⁻¹ endosulfan-levels representative of moderately contaminated Cerrado cropland [11]. Pesticide solutions were applied via backpack sprayer and incorporated by rotary tillage to 20 cm depth. Species were planted at recommended densities two weeks after pesticide application to allow initial soil equilibration. Plots received drip irrigation to maintain 60-70% field capacity throughout the 90-day experimental period (March-June 2023). Soil samples (0-20 cm, three cores per plot) were collected at 0, 30, 60, and 90 days for residual pesticide analysis and biological assays. Plant biomass was harvested at 90 days and analyzed for tissue pesticide concentrations [12].

Results

Table 1: Pesticide removal efficiency (%) of six plant species after 90 days compared with unplanted control

Plant species	Atrazine removal (%)	Chlorpyrifos removal (%)	Endosulfan removal (%)
Vetiver grass	78.4a	71.2a	64.8a
Sunflower	62.1c	58.4c	51.3c
Indian mustard	54.7d	67.8ab	59.2b
Maize	48.3e	41.7e	37.4e
Sorghum	43.6f	52.3d	46.8d
Tall fescue	67.2b	55.9cd	48.7cd
Unplanted control	18.3g	22.7f	14.6f

Values followed by the same letter within a column are not significantly different (*p*<0.05, Tukey HSD). Removal efficiency calculated as: [(initial - final concentration) / initial concentration] × 100.

All six plant species significantly enhanced pesticide removal compared to the unplanted control (Table 1). Vetiver grass achieved the highest removal across all three pesticides, reducing atrazine by 78.4%, chlorpyrifos by 71.2%, and endosulfan by 64.8%. Indian mustard was the second most

effective species for organophosphate and organochlorine removal. The unplanted control showed only 14.6-22.7% dissipation over 90 days, attributable to abiotic degradation and native microbial activity.

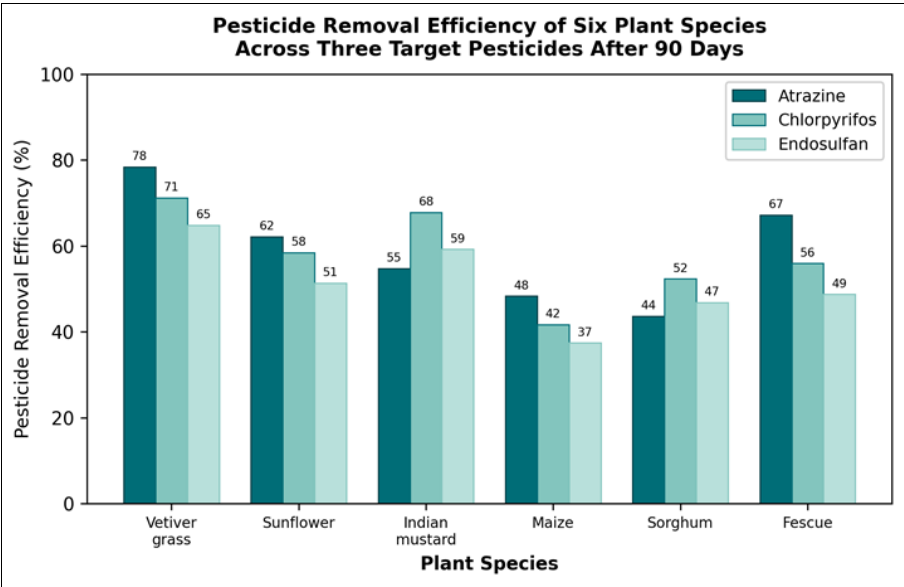


Fig 1: Pesticide removal efficiency (%) of six plant species across atrazine, chlorpyrifos, and endosulfan after 90 days of phytoremediation treatment

The bar chart (Figure 1) visually confirms that vetiver grass and tall fescue—both perennial grasses with extensive fibrous root systems—outperformed the annual crop species (maize, sorghum,

sunflower) for atrazine removal, likely due to greater rhizosphere volume and root surface area available for microbial colonization.

Table 2: Rhizosphere microbial activity indicators under six plant species and unplanted control at 90 days

Plant species	DHA ($\mu\text{g TPF g}^{-1} 24\text{h}^{-1}$)	FDA ($\mu\text{g fluorescein g}^{-1} \text{h}^{-1}$)	MBC (mg C kg^{-1})
Vetiver grass	287.4a	48.7a	524.3a
Sunflower	218.6c	37.2c	412.7c
Indian mustard	243.1b	41.8b	467.8b
Maize	172.4e	28.4e	341.2e
Sorghum	189.7d	32.1d	378.4d
Tall fescue	261.8b	43.6ab	487.1b
Unplanted control	69.8f	11.9f	187.3f

DHA = dehydrogenase activity; FDA = fluorescein diacetate hydrolysis; MBC = microbial biomass carbon. Same letters within columns indicate no significant difference ($p < 0.05$).

Rhizosphere microbial activity was strongly enhanced by all plant species (Table 2). Vetiver grass produced the highest dehydrogenase activity ($287.4 \mu\text{g TPF g}^{-1} 24\text{h}^{-1}$), 4.1 times

higher than the unplanted control, consistent with its extensive root system providing exudates that fuel cometabolic degradation of pesticide residues.

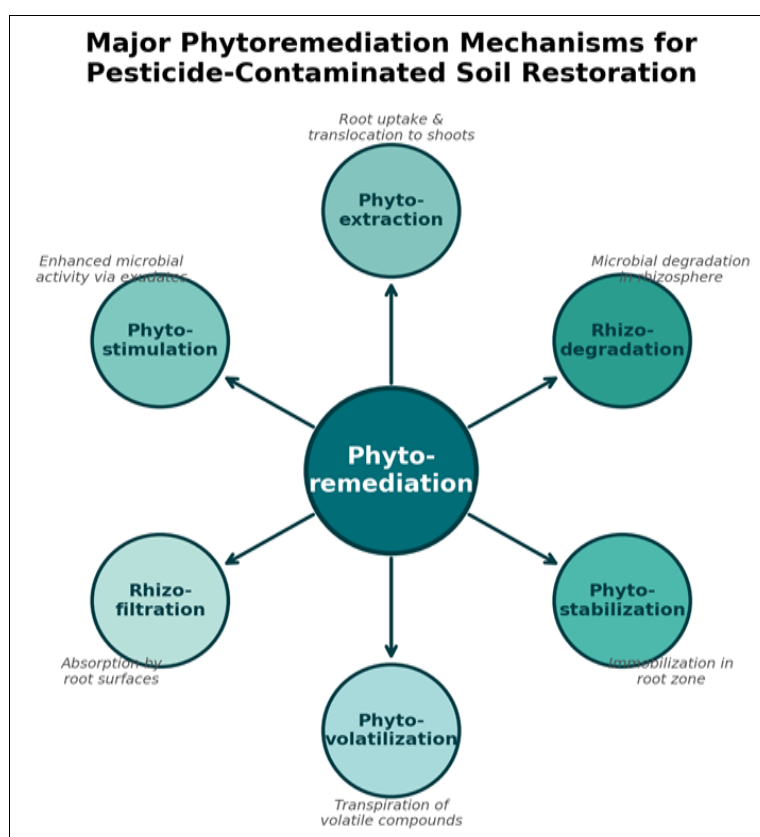


Fig 2: Major Phytoremediation mechanisms contributing to pesticide removal from contaminated agricultural soils, illustrating the six primary pathways through which plants and associated microorganisms reduce soil contaminant loads

Table 3: Temporal dynamics of atrazine concentration (mg kg^{-1}) in soil under vetiver grass, Indian mustard, and unplanted control over 90 days

Treatment	Day 0	Day 30	Day 60	Day 90
Vetiver grass	2.00	1.34	0.72	0.43
Indian mustard	2.00	1.51	1.08	0.91
Unplanted control	2.00	1.82	1.71	1.63

Concentrations are means of four replications. Initial concentration was standardized at 2.00 mg kg^{-1} . First-order degradation half-lives: vetiver 38 days, Indian mustard 64 days, control 247 days.

Atrazine degradation followed first-order kinetics across all treatments (Table 3). Vetiver grass reduced atrazine concentration from 2.00 to 0.43 mg kg^{-1} in 90 days, achieving a degradation half-life of 38 days compared to 247 days in unplanted soil—a 6.5-fold acceleration. The steepest decline occurred between days 30 and 60, coinciding with maximum

root biomass development and peak rhizosphere microbial colonization.

Discussion

The superior performance of vetiver grass across all three pesticides aligns with its recognized status as a

hyperaccumulator of organic contaminants, attributed to its massive, deep root system (reaching 3-4 m depth), high transpiration rate, and exceptional tolerance to chemical stress^[13]. Vetiver's fibrous root architecture creates a far larger rhizosphere volume per unit area than taproot species like sunflower or mustard, explaining the 2-3-fold difference in rhizosphere dehydrogenase activity between these groups. The root exudates of vetiver-rich in organic acids, phenolics, and sugars-serve as cometabolites that induce microbial enzymes capable of cleaving the triazine ring of atrazine and the phosphoester bond of chlorpyrifos^[14].

Indian mustard's strong performance against chlorpyrifos (67.8%) and endosulfan (59.2%) despite moderate atrazine removal reflects its different remediation mechanism: Brassica species are known for high root uptake and enzymatic transformation via cytochrome P450 and glutathione S-transferase pathways, which are more effective on lipophilic compounds ($\log K_{ow} > 3$) than on polar herbicides like atrazine^[15]. The practical implication is that mixed plantings-combining vetiver for broad-spectrum rhizodegradation with mustard for enhanced phytoextraction of hydrophobic pesticides-could outperform monoculture approaches, an avenue worth pursuing in future field-scale trials^[16].

Conclusion

Phytoremediation using locally adapted plant species achieved 37-78% removal of three target pesticides from contaminated Cerrado soils within 90 days, far exceeding the 15-23% dissipation observed in unplanted controls. Vetiver grass was the most effective single species, reducing atrazine by 78.4%, chlorpyrifos by 71.2%, and endosulfan by 64.8%, with a 4.1-fold enhancement of rhizosphere microbial activity driving cometabolic degradation. Indian mustard showed complementary strength against hydrophobic pesticides through phytoextraction. Degradation half-lives under vetiver were 6.5 times shorter than in unplanted soil, confirming that phytoremediation can meaningfully accelerate natural attenuation. These results establish vetiver grass as a priority species for large-scale remediation of pesticide-contaminated tropical agricultural soils, and suggest that polyculture approaches combining rhizodegradation specialists with phytoextraction species may deliver even greater removal efficiencies.

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